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from: C. C. Ong

subject: Beryllium - A Structural Material for
the Space Shuttle - Case 237

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MEMORANDUM FOR FILE

The attached Vu-graphs and associated text covering the development status and the potential structural application of beryllium were presented by this writer to a group of OMSF and OART personnel at NASA Headquarters on April 16, 1971. Discussion included the history of material development and their structural applications, materials properties, fabrication characteristics, cost, current R&D activities, potential structural application to the Space Shuttle vehicle and suggestions for future studies. Contents of the presentation, which were based on the work more comprehensively reported in "Beryllium Technology," Bellcomm TM-71-1013-2, are summarized as follows.

Utilization of beryllium as an aerospace structural material began in the mid 1950's. This material has an unusually high stiffness, unique thermal properties, and low weight. It is a good candidate material for structural elements which are buckling critical, deflection limited, require a high natural frequency, a high specific heat, or a high thermal conductivity. Its main drawbacks are brittleness, low strength and high cost. Moreover, only limited engineering experience with beryllium structure has been accumulated.

The brittleness of beryllium makes it difficult to work with. However, impressive progress in improving its ductility has been made recently, and current raw material products are considered manageable and easier to work with than are some of the advanced fiber reinforced composite materials. The material cost is high, but the overall cost of installed beryllium structure may be lower in some applications than equivalent ones made of advanced composites. The combined properties of high stiffness, low weight, high thermal conductivity and high temperature capability make beryllium competitive weightwise with other advanced materials.





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The future of beryllium as a lightweight structural material appears to be overshadowed by the rapid development of advanced composites. However, since many design and fabrication difficulties still exist in the structural application of the latter, it is believed that, with some further development, beryllium could be used advantageously for many structural elements of the Space Shuttle. A limited investment in beryllium technology to boost the soft areas of current R&D activities and to critically evaluate beryllium as a candidate material for primary as well as secondary structures appears to be a worthwhile effort. To this end the following study tasks are suggested.

1. Generation and evaluation of material property data at low temperatures.
2. Effect of meteoroid impact, particularly at low temperatures.
3. Fracture control of beryllium structures.
4. Coordination and cooperation with beryllium industry and other government agencies to generate an engineering design handbook for beryllium structures.
5. Identification of complex Space Shuttle structural components involving joints and cutouts for which beryllium can out-perform advanced composites and other engineering materials.
6. Identification of flutter critical heat shield panels in a space shuttle vehicle for which beryllium can best be applied.
7. Identification of design and fabrication problems and difficulties of beryllium primary structures for a space shuttle.
8. Tradeoff between selected structural elements using beryllium and advanced composites.

C. C. Ong
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1013-CCO-ajj

Attachments

April 16, 1971

C. C. ONG

BERYLLIUM
A STRUCTURAL MATERIAL
FOR THE SPACE SHUTTLE

BERYLLIUM ORES

BERYLLIUM, A METALLIC MATERIAL, HAS BEEN PRODUCED PRIMARILY BY EXTRACTION FROM A MINERAL CALLED BERYL, $\text{Al}_2\text{Be}_3\text{Si}_6\text{O}_{18}$, IMPORTED FROM ASIA, AFRICA AND SOUTH AMERICA. INDIA HAS BEEN THE MAJOR PRODUCER OF BERYL WHICH AMOUNTED TO ABOUT 80% OF WORLD PRODUCTION IN 1967. THE UNITED STATES HAS A BARTER ARRANGEMENT WITH INDIA WHICH PROVIDED AGRICULTURAL SURPLUS OF THE U.S. IN EXCHANGE FOR THE BERYL ORE OF INDIA.

A DOMESTIC ORE SOURCE WAS DISCOVERED IN UTAH RECENTLY AND THE BERYLLIUM INDUSTRY BEGAN TO PRODUCE BERYLLIUM HYDROXIDE IN 1969 FROM THE BERYLLIUM ORE OF UTAH CALLED BERTRANDITE, $\text{Be}_4\text{Si}_2\text{O}_7$. THE TOTAL EXTENT OF THE ORE DEPOSITE IN UTAH IS NOT KNOWN, BUT A MINIMUM OF 5 MILLION TONS HAS BEEN ESTABLISHED. THEREFORE, THERE IS NOW LITTLE SERIOUS CONCERN ABOUT THE AVAILABILITY OF THE RAW MATERIAL FOR BERYLLIUM PRODUCTION.

BERYLLIUM ORES

BERYL ($\text{AL}_2\text{BE}_3\text{Si}_6\text{O}_{18}$) FROM INDIA

BERTRANDITE ($\text{BE}_4\text{Si}_2\text{O}_7$) FROM UTAH

BERYLLIUM UTILIZATION

BERYLLIUM WAS PRIMARILY USED AS A MINOR ALLOYING ADDITION TO COPPER IN THE EARLY 1930'S. IN THE 1940'S, IT WAS FOUND THAT THE LOW ATOMIC WEIGHT AND LOW NEUTRON CAPTURE CROSS SECTION PROPERTIES OF BERYLLIUM MADE IT A GOOD MODERATOR MATERIAL IN AN ATOMIC PILE. THEREFORE, MAJOR INTEREST IN BERYLLIUM WAS EXPRESSED BY THE ATOMIC ENERGY COMMISSION FOR APPLICATIONS IN NUCLEAR REACTORS.

WITH SUCCESSFUL MANUFACTURING OF FINE GRAIN BERYLLIUM BLOCK IN THE EARLY 1950'S THE DEMAND FOR BERYLLIUM AS A STRUCTURAL MATERIAL BECAME SIGNIFICANT. SERIOUS INTEREST IN BERYLLIUM AS AN AEROSPACE STRUCTURAL MATERIAL BEGAN IN THE MID FIFTIES BECAUSE THE HIGH SPECIFIC MODULUS (MODULUS-TO-DENSITY RATIO) OF THIS MATERIAL PROMISED A GREAT WEIGHT SAVING POTENTIAL FOR CERTAIN STRUCTURAL COMPONENTS COMPARED TO ENGINEERING MATERIALS SUCH AS ALUMINUM, TITANIUM AND STAINLESS STEEL. HOWEVER, RECENT RAPID PROGRESS ON ADVANCED FIBER REINFORCED COMPOSITE MATERIALS, WHICH ALSO EXHIBIT HIGH SPECIFIC MODULUS, HAS FORCED A RE-EVALUATION OF BERYLLIUM FOR STRUCTURAL PURPOSES.

BERYLLIUM UTILIZATION

- ALLOYING ADDITION TO COPPER: 1930'S
- MODERATOR MATERIAL IN NUCLEAR REACTORS: 1940'S
- AEROSPACE STRUCTURAL MATERIAL: SINCE EARLY 1950'S

PRINCIPAL USES OF BERYLLIUM

THE PRINCIPAL USES OF BERYLLIUM AND THE RELATIVE IMPORTANCE IN TERMS OF SALES OF BERYLLIUM INDUSTRY ARE SHOWN IN THIS TABLE. THE LARGEST AMOUNT OF BERYLLIUM HAS BEEN USED FOR TARGET REENTRY VEHICLES. APPLICATIONS TO INERTIAL GUIDANCE AND INSTRUMENTATION ARE THE NEXT ON THE LIST, AND ONLY 15% HAS BEEN USED FOR OTHER AEROSPACE STRUCTURAL ITEMS.

PRINCIPAL USES OF BERYLLIUM

<u>APPLICATION</u>	<u>APPROX. % SALES</u>
RE-ENTRY VEHICLES	45
INERTIAL GUIDANCE & INSTRUMENTATION	20
NUCLEAR	15
AIRCRAFT STRUCTURE & SYSTEMS (BRAKES)	13
SPACE OPTICS	4.5
MISSILES & SPACECRAFT STRUCTURES	2
PROPULSION	0.5

IMPORTANT MATERIAL PROPERTIES

SO FAR AS STRUCTURAL APPLICATIONS ARE CONCERNED, THE MOST IMPORTANT PROPERTIES OF BERYLLIUM ARE ITS VERY HIGH SPECIFIC MODULUS (MODULUS TO DENSITY RATIO), UNIQUE THERMAL PROPERTIES, BRITTLENESS AND LOW TENSILE STRENGTH. THE SPECIFIC MODULUS IS MORE THAN SIX TIMES THOSE OF ALUMINUM, TITANIUM, AND STAINLESS STEEL AND COMPARES FAVORABLY WITH ADVANCED COMPOSITES.

BOTH THE STIFFNESS AND THE STRENGTH OF BERYLLIUM ARE LARGELY RETAINED UP TO A TEMPERATURE OF 1000°F. BERYLLIUM HAS A HIGH THERMAL CONDUCTIVITY (94 BTU/FT/HR/°F AT ROOM TEMPERATURE) WHICH HELPS TO ELIMINATE THERMAL GRADIENTS AND PROTECTS THE PART AGAINST WARPAGE AND HIGH THERMAL STRESSES. THE ROOM TEMPERATURE SPECIFIC HEAT OF BERYLLIUM (0.40 BTU/LF/°F) IS MORE THAN FOUR TIMES THAT OF STEEL AND TWICE THAT OF ALUMINUM. THE COMBINATION OF ITS THERMAL AND MECHANICAL PROPERTIES AT HIGH TEMPERATURES MAKES BERYLLIUM AN ATTRACTIVE HIGH TEMPERATURE STRUCTURAL AND HEAT SINK MATERIAL.

THE BIGGEST BARRIER TO A WIDE ACCEPTANCE OF BERYLLIUM AS A STRUCTURAL MATERIAL HAS BEEN ITS BRITTLENESS. THIS PROPERTY IS CLOSELY RELATED TO ITS LOW FRACTURE TOUGHNESS, LOW ELONGATION LIMIT AND FABRICATION DIFFICULTIES. HOWEVER, RECENT PROGRESS ON BERYLLIUM METALLURGY HAS MADE BERYLLIUM PRODUCTS MORE DUCTILE THAN EVER BEFORE. ACCORDING TO KAWECKI BERYLCO INDUSTRIES, THE CURRENT TYPICAL ROOM TEMPERATURE IN-PLANE ELONGATION LIMIT OF BERYLLIUM SHEET MATERIAL IS 15-17% AND IT IS HOPEFUL THAT A 20% ELONGATION LIMIT CAN BE REACHED IN THE NEAR FUTURE. EVEN AT THE PRESENT LEVEL, IT IS COMPARABLE TO SOME OF THE ALUMINUM AND TITANIUM ALLOYS. NEVERTHELESS, THE ELONGATION LIMIT ALONG THE SHORT TRANSVERSE DIRECTION IS STILL SMALL, ABOUT 0.5 TO 1.0%. THEREFORE, BERYLLIUM IS STILL A BRITTLE MATERIAL, BUT IT IS CONSIDERED MANAGEABLE IN FABRICATION.

ALTHOUGH BERYLLIUM HAS A VERY HIGH SPECIFIC MODULUS, ITS STRENGTH IS ONLY MODERATE AS COMPARED TO OTHER ADVANCED MATERIALS.

IMPORTANT MATERIAL PROPERTIES

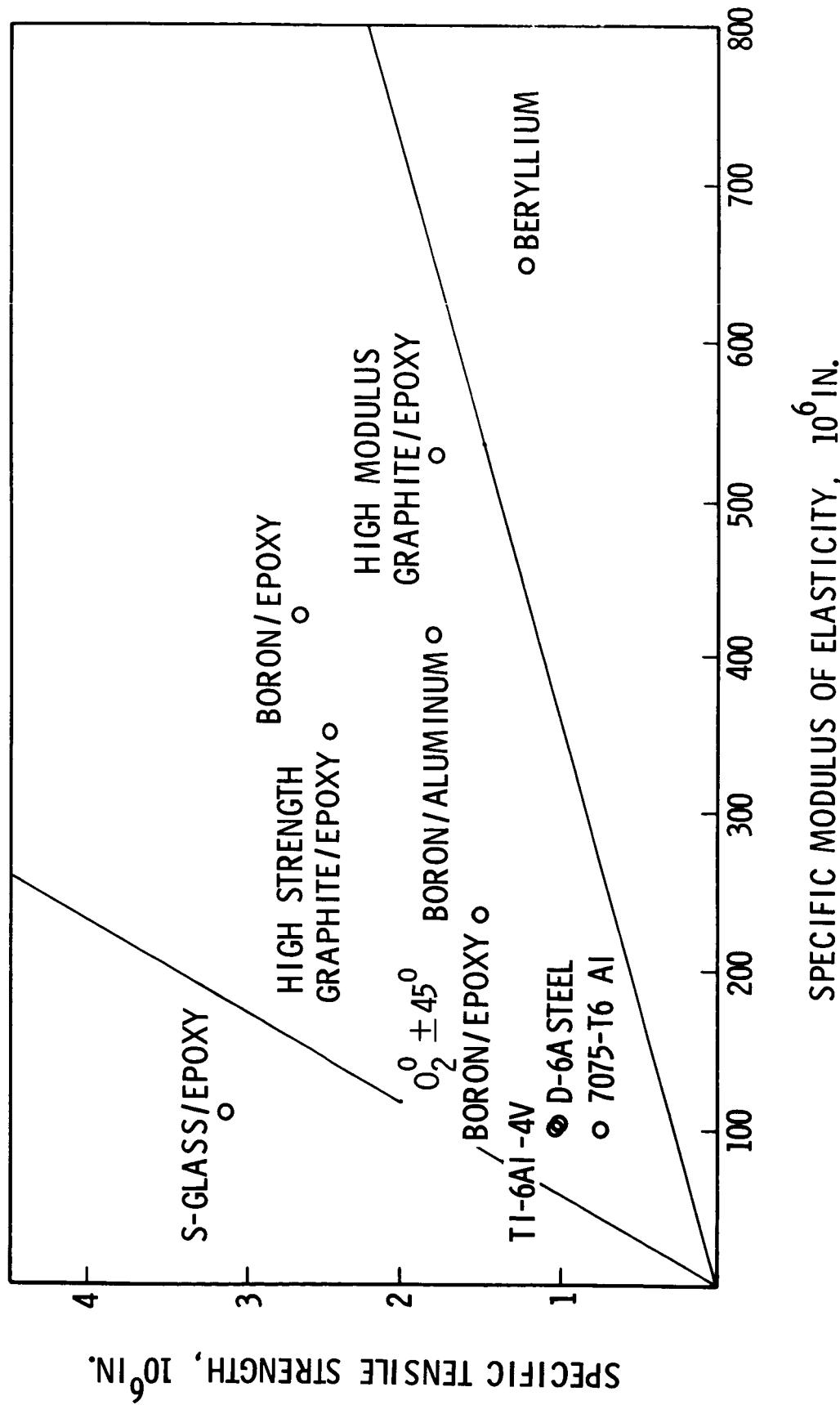
FAVORABLE PROPERTIES

- SPECIFIC MODULUS
 - SIX TIMES THOSE OF AL, TI AND STEEL
 - HIGHER THAN THOSE OF ADVANCED COMPOSITES
- THERMAL PROPERTIES
 - STRENGTH RETAINED AT HIGH TEMPERATURES
 - HIGH THERMAL CONDUCTIVITY
 - HIGH SPECIFIC HEAT
- UNFAVORABLE PROPERTIES
 - BRITTLENESS
 - LOW FRACTURE TOUGHNESS
 - LOW ELONGATION LIMIT
 - FABRICATION DIFFICULTIES
 - SPECIFIC STRENGTH
 - LOWER THAN THOSE OF ADVANCED COMPOSITES

ROOM TEMPERATURE SPECIFIC PROPERTIES OF STRUCTURAL MATERIALS

THE SPECIFIC MODULUS OF ELASTICITY AND SPECIFIC TENSILE STRENGTH OF BERYLLIUM AND SEVERAL OTHER STRUCTURAL MATERIALS ARE COMPARED IN THIS GRAPH. BERYLLIUM HAS A MODULUS OF ELASTICITY OF 44 MILLION PSI AND A DENSITY OF 0.066 LB/IN^3 . THE COMBINATION OF HIGH MODULUS AND LOW DENSITY MAKES BERYLLIUM THE MATERIAL WITH THE HIGHEST MODULUS TO DENSITY RATIO (670 MILLION INCHES) AMONG ALL STRUCTURAL MATERIALS. HOWEVER, ITS STRENGTH TO DENSITY RATIO IS LOWER THAN THOSE OF ADVANCED COMPOSITES.

ROOM TEMPERATURE SPECIFIC PROPERTIES OF STRUCTURAL MATERIALS



SPECIFIC TENSILE STRENGTH VERSUS TEMPERATURE OF STRUCTURAL MATERIALS

THIS VU-GRAF SHOWS THAT BERYLLIUM COMPARES FAVORABLY WITH ALUMINUM AND TITANIUM IN SPECIFIC STRENGTH FOR TEMPERATURES UP TO 800°F, BUT MOST OF THE ADVANCED COMPOSITES HAVE A MUCH HIGHER SPECIFIC STRENGTH THAN BERYLLIUM WITHIN TEMPERATURE LIMITS OF THEIR STRUCTURAL APPLICATIONS. THE STRENGTH LIMITATION IS ONE OF THE PRIMARY FACTORS WHICH PREVENT BERYLLIUM FROM EXTENSIVE DEVELOPMENT AND UTILIZATION AT THE SCALE OF ADVANCED COMPOSITES.

SPECIFIC TENSILE STRENGTH VERSUS TEMPERATURE
OF STRUCTURAL MATERIALS

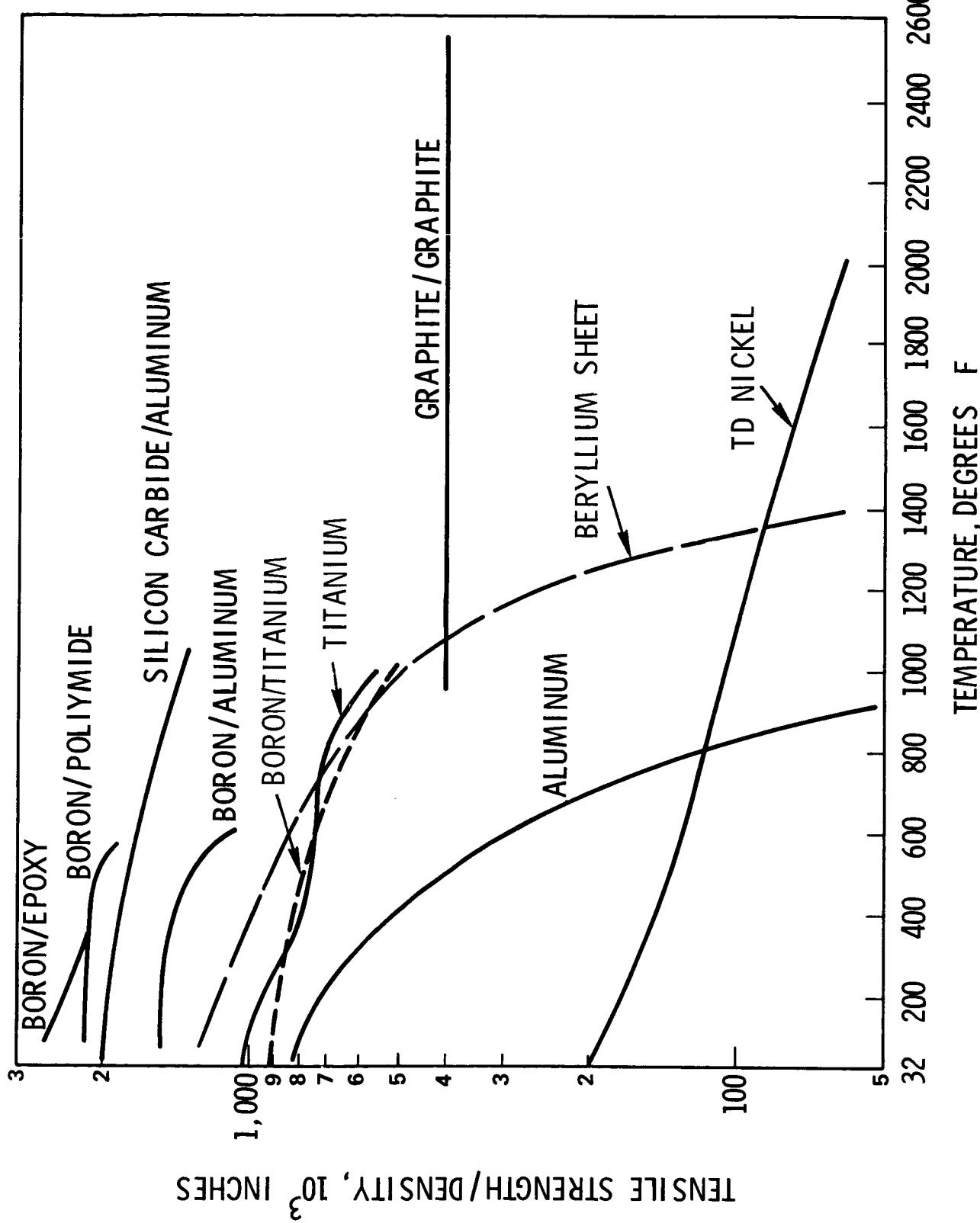


FIGURE 2 -

PRODUCT AVAILABILITY

THERE ARE THREE MAJOR BERYLLIUM SUPPLIERS IN THE UNITED STATES: THE BRUSH BERYLLIUM COMPANY, KAWECKI BERYLCO INDUSTRIES, INC. AND GENERAL ASTROMETALS, A SUBSIDIARY OF ANACONDA.

MOST OF THE BERYLLIUM OXIDE HAS BEEN USED FOR THE PRODUCTION OF BERYLLIUM COPPER ALLOYS AND TO A LESSER EXTENT FOR BERYLLIUM-ALUMINUM AND CERAMIC PRODUCTION. LESS THAN 25% HAS BEEN UTILIZED TO PRODUCE PURE BERYLLIUM METALS. BECAUSE COPPER, ALUMINUM AND OTHER BERYLLIUM ALLOYS DO NOT APPEAR TO HAVE A GREAT POTENTIAL AS ADVANCED STRUCTURAL MATERIALS, OUR DISCUSSION WILL BE LIMITED TO PURE BERYLLIUM ONLY.

A VARIETY OF PURE BERYLLIUM PRODUCTS HAVE BEEN PRODUCED FROM BLOCKS OR BILLETS MADE BY HOT VACUUM PRESSING TECHNIQUES. A METHOD DEVELOPED RECENTLY IS THE HOT ISOSTATIC PRESSING TECHNIQUE WHICH PERMITS SINTERING AND DENSIFICATION OF BERYLLIUM POWDER TO A SHAPE VERY CLOSE TO THE FINAL CONFIGURATION OF THE STRUCTURE.

SEVERAL GRADES OF HOT PRESSED BLOCKS ARE COMMERCIALLY AVAILABLE. THE SIZE OF THE PRESSINGS IN STANDARD STRUCTURAL GRADES SUCH AS THE BRUSH S-200, COULD BE AS LARGE AS 72" IN DIAMETER BY 36" HIGH, BUT THEY ARE USUALLY LIMITED TO LESS THAN 40 INCHES IN DIAMETER.

SEMIFINISHED MACHINING BLOCK IS THE MOST FREQUENTLY USED BERYLLIUM MATERIAL. IT IS USUALLY MADE FROM THE HOT PRESSED BLOCK ACCORDING TO USERS REQUIREMENTS.

FLAT PRODUCTS ARE USUALLY ROLLED FROM STANDARD STRUCTURAL GRADE BLOCKS. WITH SPECIAL ORDERS SHEETS AS WIDE AS 48" AND AS LONG AS 200" CAN BE PRODUCED. CURRENT SPECIFICATIONS CALL FOR A MINIMUM ELONGATION LIMIT OF 10% AND THE TYPICAL THICKNESS TOLERANCE IS $\pm 10\%$.

SIMPLE SHAPES OF EXTRUSIONS AND FORGINGS ARE READILY PRODUCIBLE. BUT FURTHER DEVELOPMENTAL EFFORT IS NEEDED BEFORE THESE STRUCTURAL MEMBERS BECOME PRACTICAL BECAUSE OF DIFFICULTIES ENCOUNTERED IN THE PRODUCTION PROCESS.

PRODUCT AVAILABILITY

SUPPLIERS

- BRUSH BERYLLIUM COMPANY
- KAWECKI BERYLCO INDUSTRIES
- GENERAL ASTROMETALS

PRODUCTS

HOT PRESSED BLOCK: UP TO 72" IN DIAMETER BY 36" HIGH

SEMI FINISHED MACHINING BLOCK

SHEET, PLATE AND FOIL

- SHEET: THICKNESS -- 0.020" TO 0.250"; SIZE -- 36" TO 48" X 65" TO 120"
- PLATE: THICKNESS -- 0.25" TO 0.60"; SIZE -- 40" X 35" TO 65"
- FOIL: THICKNESS -- 0.001" TO 0.020"; MAXIMUM SIZE -- 20" X 60"

EXTRUSIONS AND FORGINGS

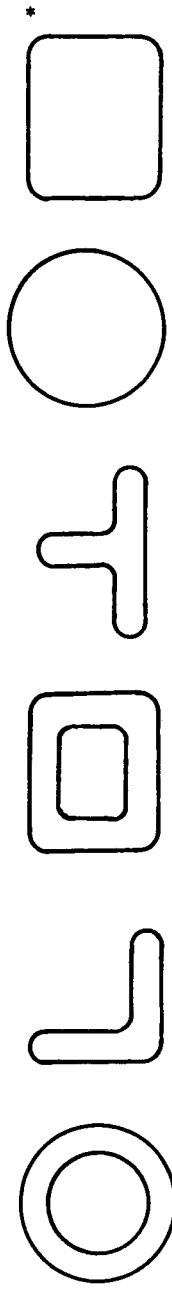
BERYLLIUM EXTRUSIONS

SOME INTERESTING EXTRUDED STRUCTURAL SHAPES AVAILABLE ARE SHOWN IN THIS TABLE. THE DEVELOPMENT OF PRODUCTION PROCESSES FOR THE EXTRUSIONS IS OFTEN TROUBLESOME AND CONTROL OF CROSS-SECTIONAL DIMENSIONS IS DIFFICULT BECAUSE THE EXTRUSION BILLETS MUST BE CLAD TO PREVENT GALLING OF BERYLLIUM ON EXTRUSION TOOLS.

FORGINGS ARE IN A COMPARABLE STAGE OF DEVELOPMENT. AT PRESENT FORGING IS APPLIED ONLY TO IMPROVE THE PROPERTIES AT THE EXPENSE OF HIGH COST.

BERYLLIUM EXTRUSIONS

WIDTH AND DEPTH OR DIAMETER	1/4" TO 8"	3/4" TO 3"	3/4" TO 3"	0.100" MIN. TO 5 1/4" MAX.	2 1/2" TO 10" WIDE
THICKNESS	0.040 TO 0.750	0.060 TO 0.500	0.060 TO 0.500	0.060 TO 0.500	1/8" TO 1/2" THICK



* MAXIMUM GROSS SECTIONAL AREA AVAILABLE IS 20 SQUARE INCHES

FABRICATION

BERYLLIUM IS NOT FORGIVING, AND THE FABRICATOR HAS TO UNDERSTAND THE EXACT PROCESS REQUIRED FOR ITS FABRICATION. EXTRAORDINARY CONTROL WITH RESPECT TO MACHINING OPERATIONS HAS TO BE EXERCISED TO INSURE A STRUCTURALLY SOUND PRODUCT. HOWEVER, BERYLLIUM IS MANAGEABLE IN FABRICATION AND RECENT IMPROVEMENT ON MATERIAL DUCTILITY HAS PLACED BERYLLIUM IN A RELATIVELY BETTER POSITION FOR FABRICATION THAN OTHER ADVANCED MATERIALS SUCH AS ADVANCED COMPOSITES.

THE BRITTLE BERYLLIUM IS PRONE TO CHIPOUT, CRACKING AND SPALLING. PERHAPS THE MOST DIFFICULT FABRICATION PROBLEM OF BERYLLIUM IS DRILLING DEFECT-FREE HOLES. ALTHOUGH SEVERAL TECHNIQUES HAVE BEEN DEVELOPED, HOLE DRILLING REMAINS A COSTLY PROCESS.

BRAZING TECHNOLOGY FOR BERYLLIUM IS WELL DEVELOPED. FOR LOW TEMPERATURE SERVICE ZINC BRAZING HAS BEEN SUCCESSFULLY USED. AS THE SERVICE TEMPERATURE INCREASES ALUMINUM BASE BRAZING, SILVER-COPPER BASE BRAZING OR SILVER BRAZING SHOULD BE APPLIED. BONDING HAS ALSO BEEN USED SUCCESSFULLY. EPOXY-PHENONIC ADHESIVE CAN PROVIDE GOOD ROOM TEMPERATURE SHEAR STRENGTH AND RETAIN A PORTION OF IT AT TEMPERATURES UP TO 600°F.

DIFFUSION BONDING FOR BERYLLIUM IS CURRENTLY BEING DEVELOPED BY NORTH AMERICAN ROCKWELL. PRELIMINARY COMPRESSION TESTS REVEALED EXCELLENT LOAD CAPABILITY AND JOINT INTEGRITY. THIS JOINING TECHNIQUE IS CONSIDERED PROMISING.

BERYLLIUM PRODUCTS CAN BE FORMED INTO MANY COMPLEX CONFIGURATIONS. THE OPTIMUM FORMING TEMPERATURE USED TO BE AROUND 1350°F FOR A VARIETY OF CONFIGURATIONS SUCH AS STRAIGHT BEND, CURVED CHANNELS, HEMISPHERICAL SEGMENTS, AND SEMICYLINDER WITH SPHERICAL ENDS. RECENT IMPROVEMENT IN MATERIAL DUCTILITY HAS GREATLY FACILITATED THE FORMING OF BERYLLIUM ELEMENTS. CURRENT PRODUCTS PERMIT FORMING AT TEMPERATURES AS MUCH AS 500°F BELOW THE ABOVE MENTIONED FORMING TEMPERATURE. A MINIMUM BEND RADIUS OF 5 TIMES ITS THICKNESS HAS BEEN ACHIEVED FOR CROSS-ROLLED BERYLLIUM SHEET.

FABRICATION

- MACHINING
 - TOXICITY
 - TWINNING
 - CHIPOUT AND SPALLING
- JOINING
 - BRAZING AND ADHESIVE BONDING: MOST APPROPRIATE TECHNIQUES AVAILABLE
 - WELDING: DIFFICULT
 - DIFFUSION BONDING: PROMISING
- FORMING
 - COMPLEX CONFIGURATION POSSIBLE
 - HIGH FORMING TEMPERATURE
 - MINIMUM BEND RADIUS: 5T

COST

THE HIGH COST OF BERYLLIUM MATERIAL AND ITS FABRICATION HAS BEEN GENERALLY CONSIDERED ONE OF THE MAJOR DRAWBACKS WHICH PREVENT THIS MATERIAL FROM EXTENSIVE UTILIZATION IN PRIMARY AEROSPACE VEHICLE STRUCTURES. HOWEVER, SUBSTANTIAL COST REDUCTION HAS BEEN ACHIEVED RECENTLY, PARTICULARLY FOR SHEET PRODUCTS AND THEIR FABRICATION, WHICH HAS ENHANCED THE ATTRACTIVENESS OF THIS MATERIAL.

MATERIAL COST

- HOT PRESSED BLOCK:
 - \$50-70/LB
- SEMIFINISHED MACHINING BLOCK:
 - \$350/LB FOR 1/4" THICK CONE
 - \$105/LB FOR 1" THICK CONE
- SHEET:
 - \$465/LB FOR 0.020" THICK SHEET
 - \$120/LB FOR 0.25" THICK SHEET

ENGINEERING EXPERIENCE

A NUMBER OF RESEARCH AND DEVELOPMENT AS WELL AS APPLICATION PROGRAMS OF BERYLLIUM HAVE BEEN CONDUCTED IN THE PAST 10 YEARS. SEVERAL STRUCTURAL APPLICATION PROGRAMS WHICH MAY SERVE TO ILLUSTRATE THE APPLICABILITY OF BERYLLIUM TO THE SPACE SHUTTLE VEHICLE ARE LISTED. STRUCTURAL PROGRAMS ASSOCIATED WITH NUCLEAR WEAPONS ARE EXCLUDED DUE TO THE CLASSIFIED NATURE OF THE INFORMATION. NON-STRUCTURAL APPLICATIONS TO INERTIAL GUIDANCE AND INSTRUMENTATION ARE NOT INCLUDED EITHER.

IT SHOULD BE POINTED OUT THAT THERE HAVE BEEN MANY OTHER EXPERIMENTAL STUDIES OF BERYLLIUM STRUCTURAL COMPONENTS, MANY OF WHICH WERE GROUND TESTED OR FLIGHT TESTED, BUT ONLY A FEW USED IN PRODUCTION.

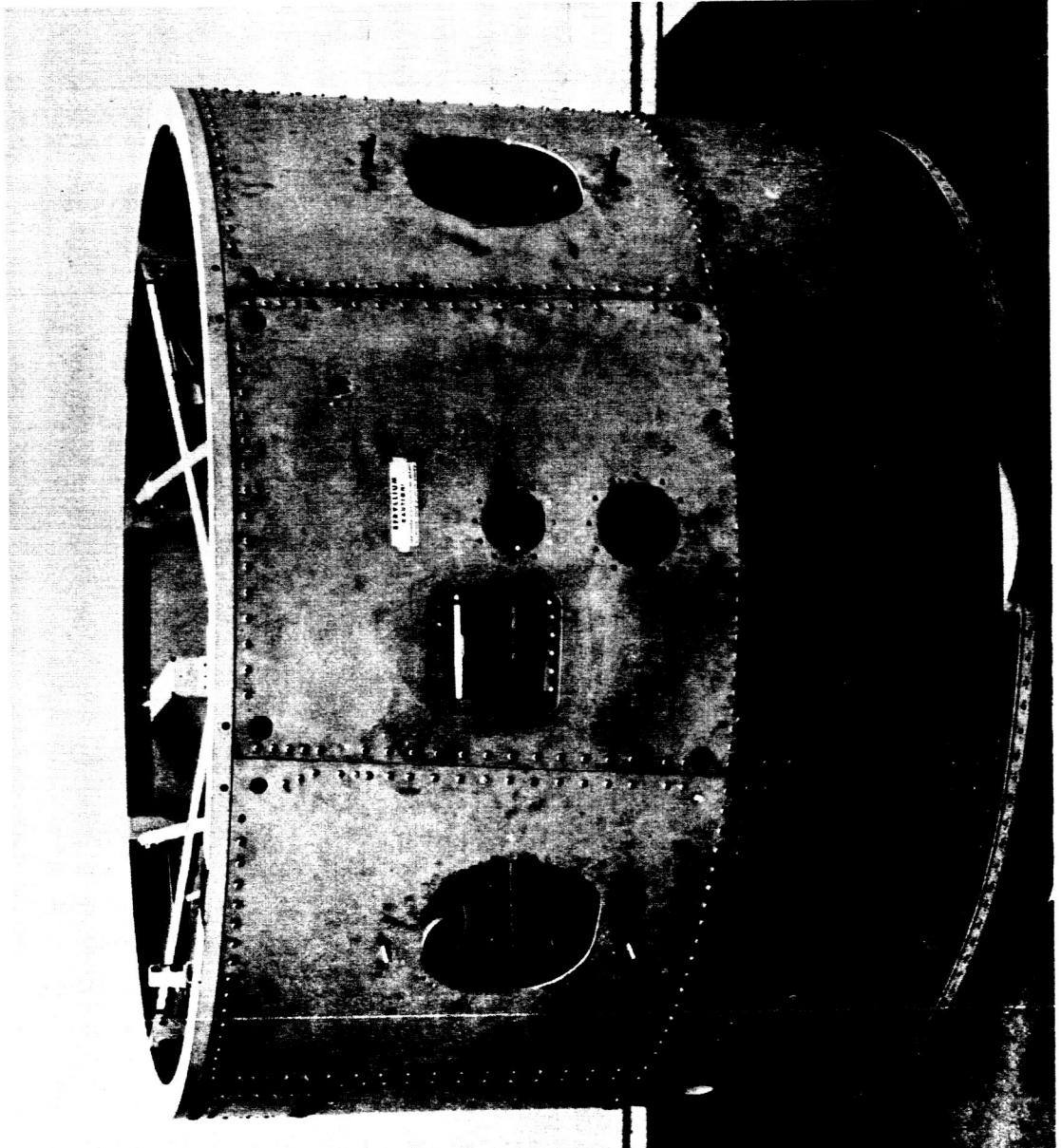
ENGINEERING EXPERIENCE

<u>PROGRAMS</u>	<u>GROUND TESTED</u>	<u>FLIGHT TESTED</u>	<u>PRODUCTION ITEM</u>
• AGENA SPACECRAFT FORWARD EQUIPMENT SECTION			X
• MINUTEMAN BERYLLIUM SPACER			X
• SHINGLES OF MERCURY AND GEMINI SPACECRAFTS		X	
• SATELLITE STRUCTURAL ASSEMBLIES		X	
• STIFFENER STRAPS FOR F-14 AIRCRAFT		X	
• F-4 RUDDER	X		
• BRAKE DISKS OF C-5A, F-4 AND A-3 AIRCRAFTS		X	
• AEROSPACE PLANE WING BOX	X		
• RING FRAME SEGMENT WITH I-BEAM CROSS SECTION		X	

AGENA FORWARD EQUIPMENT SECTION

SKIN PANELS MADE OF CROSS-ROLLED BERYLLIUM SHEET WERE USED TO REPLACE MAGNESIUM ALLOY ON THE LOCKHEED AGENA D FORWARD EQUIPMENT SECTION WHICH IS A RIGHT CYLINDER 60 INCHES IN DIAMETER AND 40 INCHES IN HEIGHT. THIS WAS A STRUCTURAL RE-DESIGN WHICH LED TO A SIGNIFICANT WEIGHT REDUCTION. THE BASIC PANEL IS 0.050 INCHES THICK WITH THICKENED EDGES FORMED BY CHEMICAL MILLING. THE PANEL ATTACHMENT DESIGN WAS A SIMPLE LAP JOINT USING TITANIUM SCREWS IN COMBINATION WITH THE THICKENED EDGE. THE FIRST AGENA CARRYING A BERYLLIUM SKINNED FORWARD EQUIPMENT SECTION WAS SUCCESSFULLY LAUNCHED IN JUNE 1964. LATER, ABOUT 3500 BERYLLIUM PANELS USED IN 168 AGENA SPACECRAFT WERE MADE IN SEVEN YEARS OF CONTINUOUS PRODUCTION.

AGENA FORWARD EQUIPMENT SECTION

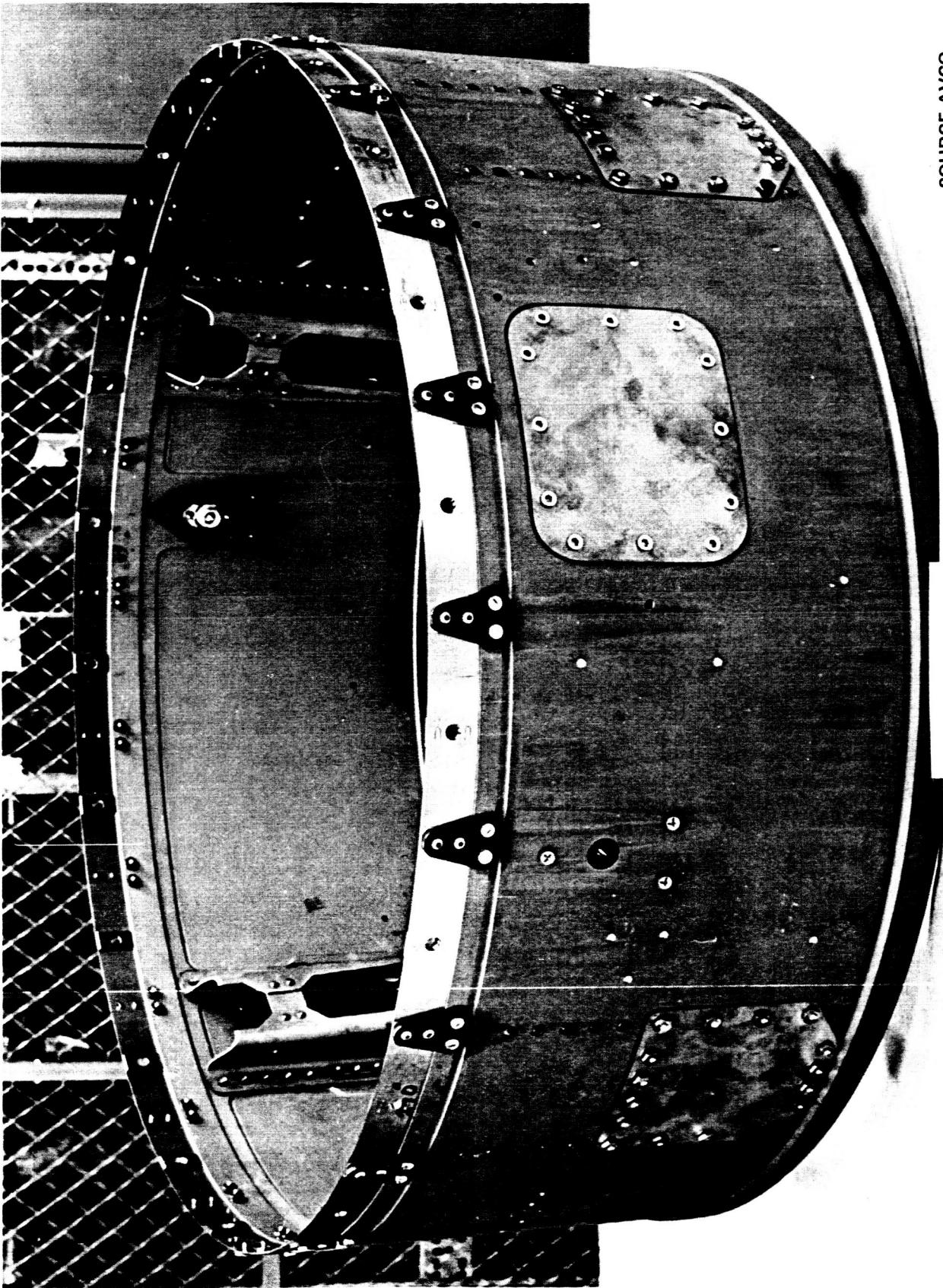


SOURCE LMSC

THE MINUTEMAN BERYLLIUM SPACER

THE DESIGN AND FABRICATION OF A BERYLLIUM SPACER SERVING AS THE INTERSTAGE SECTION BETWEEN THE REENTRY VEHICLE AND THE GUIDANCE AND CONTROL SECTION OF THE MINUTEMAN BOOSTER WAS INITIATED IN 1962 AT AVCO. THE SPACER, ABOUT 32 INCHES IN DIAMETER AND 12.5 INCHES LONG WAS A DIRECT SUBSTITUTION FOR AN EXISTING ALUMINUM-HEAT SHIELD COMPOSITE STRUCTURE. IT WAS MADE FROM A STRESS RELIEVED RING-ROLLED FORGING HAVING A SHELL THICKNESS OF 0.080 INCHES WHICH WAS REQUIRED FOR HEAT ABSORPTION DURING ASCENT WITHOUT A HEAT SHIELD. FOUR BERYLLIUM LONGERONS LOCATED 90° APART WERE RIVETED AND BONDED TO THE SHELL STRUCTURE. THERE WERE ALSO FIVE CUT-OUTS IN THE BASIC SHELL STRUCTURE. THE BERYLLIUM STRUCTURE WEIGHED 10.2 LBS AGAINST 25 LBS OF THE ORIGINAL ALUMINUM SHELL AND WAS ABOUT 30.5% THE WEIGHT OF THE COMBINED ALUMINUM SHELL AND ITS HEAT SHIELD.

THE BERYLLIUM SPACER

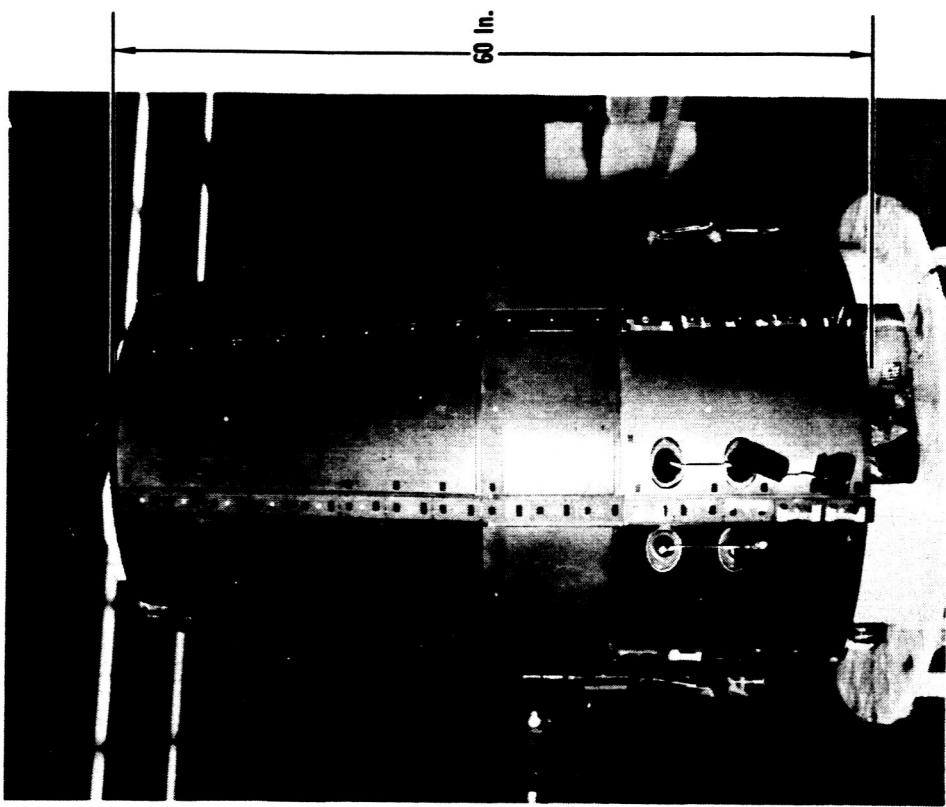


SOURCE AVCO

BERYLLIUM SHINGLES FOR MERCURY AND GEMINI SPACECRAFT

BERYLLIUM WAS SELECTED FOR EXTERNAL HEAT PROTECTION ON THE UPPER CYLINDRICAL SECTION OF MERCURY AND GEMINI SPACECRAFTS. THESE HEAT SHIELDS UNIFORMLY DISSIPATED THE HEAT PULSE CAUSED BY IMPINGEMENT OF THE CORNER SHOCK WAVE REATTACHMENT. THE 12 SHINGLES FOR EACH MERCURY SPACECRAFT WERE MANUFACTURED FROM S-200-A HOT PRESSED BLOCK. THE 0.23 INCH THICKNESS OF THE SHINGLE WAS REQUIRED FOR HEAT SINK WHILE A MAXIMUM TEMPERATURE OF 1300°F WAS REACHED DURING REENTRY. THE 24 SHINGLES FOR EACH GEMINI SPACECRAFT WERE MANUFACTURED FROM CROSS-ROLLED BERYLLIUM PLATE AND HAD A THICKNESS VARYING FROM 0.07 INCHES TO 0.28 INCHES, ALSO DICTATED BY THE HEAT SINK REQUIREMENT.

BERYLLIUM SHINGLES OF GEMINI SPACECRAFT

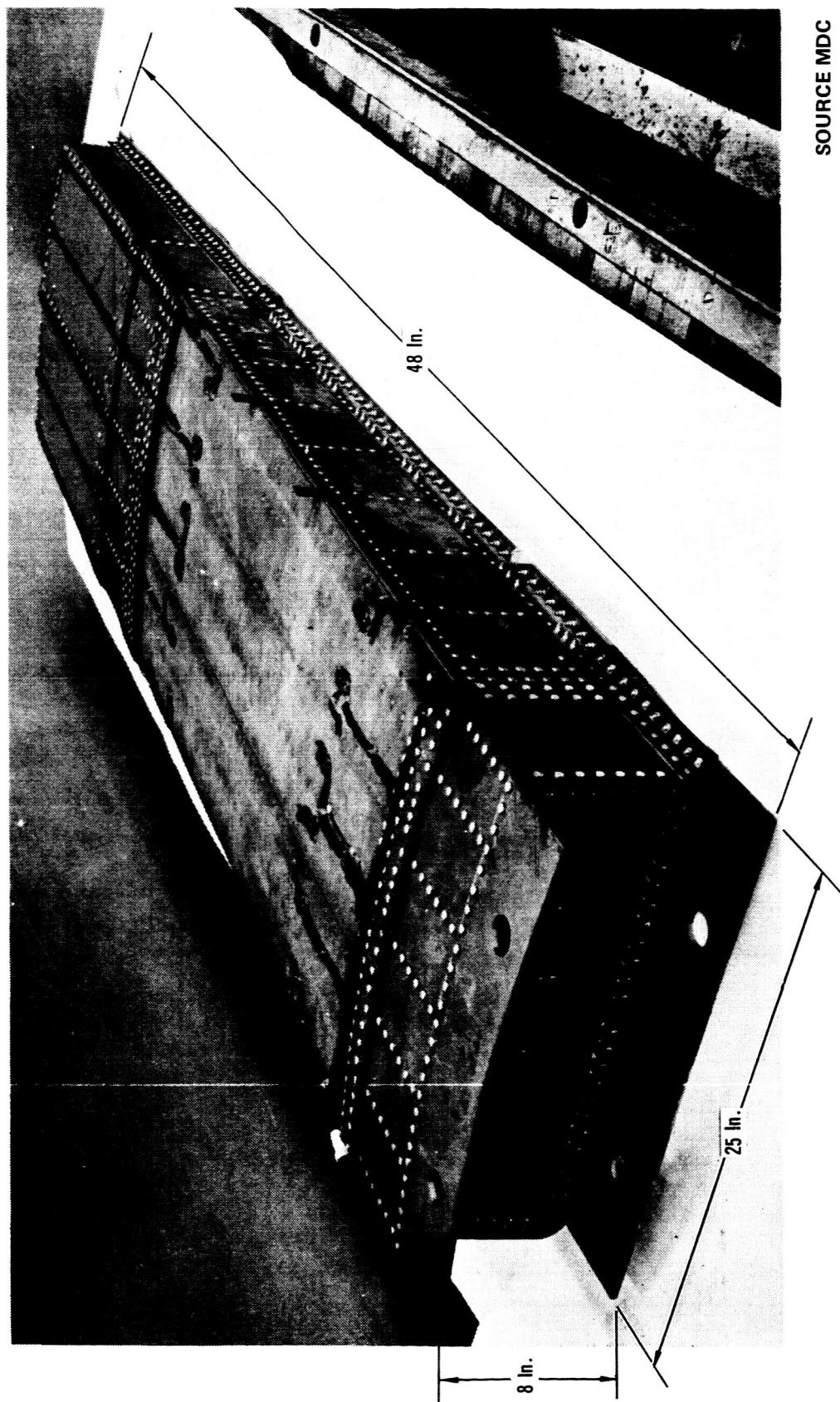


SOURCE MDC

BERYLLIUM WING BOX

TWO WING BOXES, FOR AN AEROSPACE PLANE, EACH 48 INCHES LONG, 25
INCHES WIDE AND 6 TO 8 INCHES DEEP WERE FABRICATED AND GROUND TESTED BY THE
MCDONNELL DOUGLAS CORPORATION. THE PROGRAM DEMONSTRATED THE FEASIBILITY OF
COMPLEX AEROSPACE STRUCTURAL COMPONENTS OF BERYLLIUM AND THE PREDICTABILITY
OF ITS STRENGTH LEVEL.

BERYLLIUM WING BOX

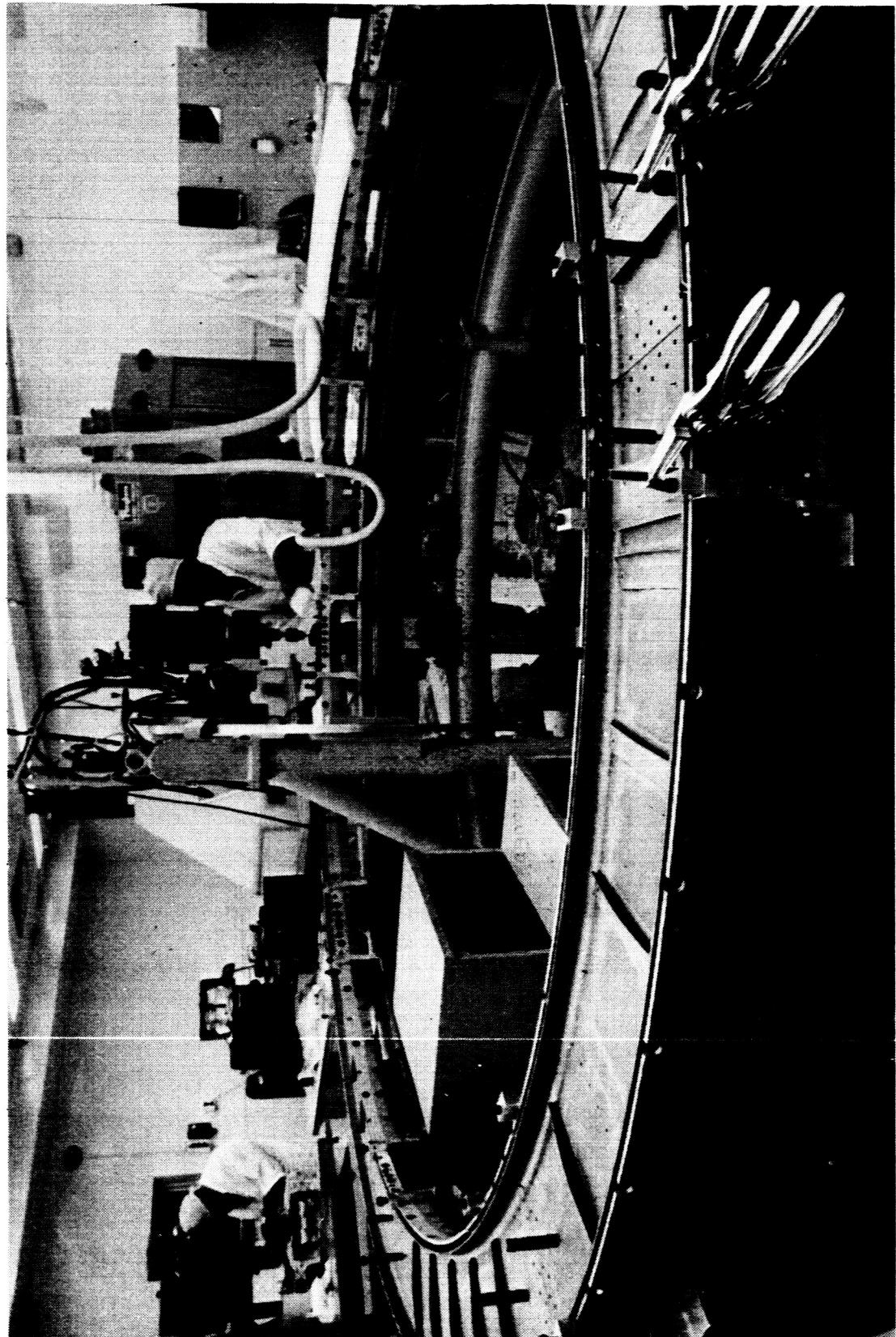


SOURCE MDC

BERYLLIUM FRAME

A BERYLLIUM STRUCTURAL RING FRAME SEGMENT MADE UP AS A I BEAM WITH BERYLLIUM CAPS AND ALUMINUM SHEAR WEBS JOINED BY MECHANICAL FASTENERS WAS DESIGNED FOR A MANNED SPACECRAFT BY THE MCDONNELL DOUGLAS CORPORATION. HERE BERYLLIUM WAS CHOSEN TO MEET THE LIMITED SPACE AVAILABLE FOR FRAME DEPTH WHILE PROVIDING THE HIGH STIFFNESS REQUIRED. FOR THESE REQUIREMENTS ALUMINUM OR STEEL ALLOY DESIGNS WERE IMPOSSIBLE OR WEIGHTWISE IMPRACTICAL.

BERYLLIUM FRAME



SOURCE MDC

POTENTIAL STRUCTURAL APPLICATIONS

BERYLLIUM, POSSESSING A HIGH SPECIFIC MODULUS, IS PARTICULARLY SUITABLE FOR STRUCTURES WHICH ARE BUCKLING CRITICAL, DEFLECTION LIMITED, AND DESIGNED FOR A HIGH NATURAL FREQUENCY. DUE TO ITS UNIQUE THERMAL PROPERTIES BERYLLIUM CAN BE USED ADVANTAGEOUSLY FOR STRUCTURES WHICH ARE THERMAL CONDUCTION CONTROLLED, OR THERMAL EXPANSION SENSITIVE. IT IS ALSO AN IDEAL CHOICE FOR NON-STRUCTURAL COMPONENTS OR LIGHTLY LOADED STRUCTURES WHICH CAN TAKE FULL ADVANTAGE OF ITS HIGH-STIFFNESS, HIGH TEMPERATURE RESISTANT CAPABILITY, HIGH SPECIFIC HEAT, OR HIGH THERMAL CONDUCTIVITY.

POTENTIAL STRUCTURAL APPLICATIONS

STRUCTURAL COMPONENTS REQUIRING HIGH MODULUS

- CYLINDRICAL COLUMN
- CANTILEVER BEAM
- COMPRESSION PANEL
- PANELS VULNERABLE TO FLUTTER OR BUFFETING
- GUIDANCE AND CONTROL COMPONENTS

STRUCTURES REQUIRING HIGH TEMPERATURE CAPABILITY, HIGH THERMAL CONDUCTIVITY AND HIGH SPECIFIC HEAT

- THERMAL PROTECTION SYSTEM
- BRAKE DISK

SPACE SHUTTLE APPLICATION

A PRELIMINARY STUDY ON STRUCTURAL APPLICATIONS OF BERYLLIUM FOR A SPACE SHUTTLE ORBITER WAS CONDUCTED BY LOCKHEED MISSILES AND SPACE COMPANY. BY USING BERYLLIUM FOR BODY SHELLS AND FRAMES, AERODYNAMIC SURFACES INCLUDING FINS, RUDDERS AND FLAPS AND THERMAL PROTECTION SYSTEMS, A TOTAL WEIGHT SAVING AS MUCH AS 30,000 LBS COULD BE ACHIEVED FOR AN ORBITER.

IN A MORE RECENT REPORT LOCKHEED CLAIMED THAT BY REDESIGNING THE ORBITER USING BERYLLIUM FOR PRIMARY STRUCTURES, THE SIZE OF THE VEHICLE WOULD BE REDUCED SIGNIFICANTLY. AS MUCH AS 40%, OR MORE THAN 70,000 LBS, OF THE ORBITER DRY WEIGHT COULD BE SAVED AS COMPARED WITH AN ALUMINUM/TITANIUM DESIGN. THE TOTAL SYSTEM LAUNCH WEIGHT OF A TWO STAGE FULLY REUSABLE VEHICLE COULD BE REDUCED FROM 3.5 MILLION LBS TO 2.5 MILLION LBS.

SPACE SHUTTLE APPLICATION

SELECTED APPLICATION OF BERYLLIUM

- FINS, RUDDERS AND FLAPS: 2.4 LB/FT^2 SAVING FROM AN ALUMINUM DESIGN WITH HEAT SHIELDS
- THERMAL PROTECTION SYSTEM: 0.75 LB/FT^2 SAVING FROM A TITANIUM DESIGN
- BODY SHELLS AND FRAMES: 1 LB/FT^2 SAVING FROM AN ALUMINUM DESIGN
- TOTAL WEIGHT SAVING: 30,000 LBS FOR AN ORBITER

BERYLLIUM FOR ALL PRIMARY STRUCTURES

- ORBITER WEIGHT SAVING: 70,000 LBS OR 40%
- TOTAL SYSTEM LAUNCH WEIGHT: REDUCED FROM 3.5 M LBS TO 2.5 M LBS

SOURCE: LMSC

BERYLLIUM VERSUS ADVANCED COMPOSITES

THE TECHNOLOGY OF ADVANCED COMPOSITES HAS BEEN ADVANCING SO RAPIDLY THAT MANY AEROSPACE ENGINEERS AND MANAGERS HAVE COME TO HINGE THEIR HOPES FOR STRUCTURAL WEIGHT REDUCTION ON THE APPLICATION OF SUCH MATERIALS AS BORON/EPOXY, GRAPHITE/EPOXY, OR BORON/ALUMINUM. THE FUTURE OF BERYLLIUM AS A LIGHTWEIGHT STRUCTURAL MATERIAL, THEN, WILL INEVITABLY DEPEND TO A GREAT EXTENT ON ITS COMPETITIVE POSITION WITH ADVANCED COMPOSITES. AS MENTIONED EARLIER, NO DIRECT TRADEOFF STUDY ON STRUCTURAL DESIGN USING BERYLLIUM VERSUS ADVANCED COMPOSITES WAS FOUND IN THE LITERATURE. HOWEVER, A QUALITATIVE COMPARISON BASED ON MATERIAL PROPERTIES IS IN ORDER.

PROBABLY THE MOST IMPORTANT FACTOR UNFAVORABLE TO BERYLLIUM IS THE EXTENSIVE RESEARCH AND DEVELOPMENT PROGRAM ON ADVANCED COMPOSITES CURRENTLY UNDERWAY. THE PROGRESS TO BE MADE IN THE NEAR FUTURE ON THE IMPROVEMENT OF MATERIAL PROPERTIES, FABRICATION PROCESS AND COST REDUCTION FOR ADVANCED COMPOSITES WOULD CONCEIVABLY BE FASTER THAN FOR BERYLLIUM. HOWEVER, AT THE PRESENT STATE OF TECHNOLOGY BERYLLIUM MAY HAVE FABRICATION AND WEIGHT ADVANTAGES OVER ADVANCED COMPOSITES IN MANY APPLICATIONS.

BERYLLIUM VERSUS ADVANCED COMPOSITES

ADVANTAGES OF BERYLLIUM:

1. HIGH SPECIFIC MODULUS
2. HIGH TEMPERATURE CAPABILITY AND THERMAL CONDUCTIVITY
3. A HOMOGENEOUS AND MORE OR LESS ISOTROPIC MATERIAL
4. LOW FABRICATION COST FOR MANY APPLICATIONS, PARTICULARLY FOR STRUCTURES WITH JOINTS AND CUT-OUTS.

ADVANTAGES OF ADVANCED COMPOSITES:

1. HIGH SPECIFIC STRENGTH
2. SUPERIOR FRACTURE CHARACTERISTICS
3. LOW MATERIAL COST (IN CERTAIN CASES)
4. RAPID TECHNOLOGICAL ADVANCEMENT

CURRENT R&D PROGRAMS

DUE TO OVERALL CUTBACK OF R&D FUNDS, GOVERNMENT SPONSORED ACTIVITIES OF BERYLLIUM TECHNOLOGY HAVE BEEN DECREASING STEADILY. ON THE OTHER HAND, THE R&D PROGRAMS INITIATED BY BERYLLIUM PRODUCERS HAVE INCREASED SOMEWHAT. IT WAS ESTIMATED THAT BERYLLIUM PRODUCERS ARE CURRENTLY SPENDING ABOUT 3 MILLION DOLLARS PER YEAR ON R&D. MOST OF THE CURRENT PROGRAMS ARE DIRECTED TOWARD THE IMPROVEMENT OF MANUFACTURING TECHNIQUES, IMPROVEMENT OF FABRICABILITY, AND COST REDUCTION AS WELL AS THE DEFINITION OF STRUCTURAL APPLICATIONS. VERY FEW ARE DEVOTED TO BASIC UNDERSTANDING OF BERYLLIUM MATERIAL WHICH IS FELT TO BE NECESSARY TO FORM A BASIS FOR LONG TERM PRODUCT IMPROVEMENT. IMPORTANT CURRENT PROGRAMS ARE LISTED HERE AND ON THE FOLLOWING CHART.

CURRENT BERYLLIUM R&D PROGRAMS

PRIMARY GOAL	PROGRAMS	SPONSOR	CONTRACTOR(S)
IMPROVEMENT OF MANUFACTURING TECHNIQUE	1. EXTENSION OF HOT-ISOSTATIC-PRESSING TECHNOLOGY TO FABRICATE THIN-WALLED SHAPES 2. PRODUCTION OF VERY FINE BERYLLIUM POWDERS BY THE AMELGAM PROCESS 3. DEVELOPMENT OF A METHOD FOR THE PRODUCTION OF BARE EXTRUSION 4. IMPROVEMENT OF INGOT SHEET BY DEVELOPING BARE ROLLING TECHNIQUE 5. PROCESSING CONTROL OF THE POWDER METALLURGY PRODUCTS	MANUFACTURING TECHNOLOGY DIV., WRIGHT-PATTERSON AIR FORCE BASE NASA	BATTELLE MEMORIAL INSTITUTE GENERAL ASTROMETALS
IMPROVEMENT OF PRODUCT FABRICABILITY	1. SOLID-STATE DIFFUSION BONDING WROUGHT PRODUCT 2. FABRICATION OF POROUS BERYLLIUM STRUCTURES 3. EVALUATION OF A NEW DRILL DESIGN FOR HOLE ALIGNMENT 4. HOT-ISOSTATIC-PRESSING PROCESS TO PRODUCE LARGE NEARLY NET SHAPES 5. SHEAR FORMING OF S-120 BERYLLIUM INTO CONICAL AND OTHER SHAPES	AIR FORCE MATERIALS LABORATORY (AFML) AFML	BOEING AND BATTELLE McDONNELL-DOUGLAS AND BRUSH BERYLLIUM PHILCO-FORD

CURRENT BERYLLIUM R & D PROGRAMS (CONTINUED)

PRIMARY GOAL	PROGRAMS	SPONSOR	CONTRACTOR
IMPROVEMENT OF MATERIAL PROPERTIES	1. EXPERIMENTAL STUDY OF THE EFFECTS OF GRAIN SIZE, PREFERRED ORIENTATION AND OXIDE CONTENTS ON THE TENSION, TORSIONAL AND BIAXIAL STRAIN PROPERTIES 2. DEVELOPMENT OF A NEW LOW-ALLOY ADDITION SHEET WITH BETTER HANDLING CHARACTERISTICS AND FRACTURE-TOUGHNESS PROPERTIES 3. IMPROVED MATERIAL FOR BRAKE APPLICATION 4. CHARACTERIZATION OF A NEW POWDER-METALLURGY SHEET	AFML KBI	SOUTHWEST RESEARCH INSTITUTE
IMPROVEMENT OF SIZE AND COST OF BERYLLIUM PRODUCTS	1. PRODUCTION OF SMALL-DIAMETER WIRE BY HYDRAULIC PROCESS 2. APPLICATION OF ISOPRESSING AND SINTERING AS A PRIMARY CONSOLIDATION STEP TO PRODUCE CHEAPER BLANKS AND PROVIDES IN-PROCESS CONTROL	MANUFACTURING TECHNOLOGY DIR. WRIGHT-PATTERSON AIR FORCE BASE KBI & BRUSH BERYLLIUM	MCDONNELL-DOUGLAS
STRUCTURAL APPLICATION	1. COST-EFFECTIVE STUDY ON BERYLLIUM STRUCTURES FOR ADVANCED AIRCRAFT 2. DEVELOPMENT OF DAMAGE TOLERANT BERYLLIUM STRUCTURES 3. BERYLLIUM STRUCTURES FOR THE SPACE SHUTTLE	AIR FORCE FLIGHT DYNAMICS LABORATORY (AFFDL) AFFDL LOCKHEED MISSILES AND SPACE COMPANY	NORTH AMERICAN ROCKWELL

ASSESSMENT OF CURRENT TECHNOLOGY

BERYLLIUM IS A STRUCTURAL MATERIAL WHICH HAS UNUSUALLY HIGH STIFFNESS, UNIQUE THERMAL PROPERTIES, AND LOW WEIGHT. IT IS A GOOD CANDIDATE MATERIAL FOR STRUCTURAL ELEMENTS WHICH ARE BUCKLING CRITICAL, DEFLECTION LIMITED, REQUIRE A HIGH NATURAL FREQUENCY, A HIGH SPECIFIC HEAT, OR A HIGH THERMAL CONDUCTIVITY. ITS MAIN DRAWBACKS ARE BRITTLENESS, LOW STRENGTH AND HIGH COST. MOREOVER, ONLY LIMITED ENGINEERING EXPERIENCE WITH BERYLLIUM STRUCTURE HAS BEEN ACCUMULATED.

THE BRITTLENESS OF BERYLLIUM MAKES IT DIFFICULT TO WORK WITH. HOWEVER, IMPRESSIVE PROGRESS IN IMPROVING ITS DUCTILITY HAS BEEN MADE RECENTLY, AND CURRENT RAW MATERIAL PRODUCTS ARE CONSIDERED MANAGEABLE AND EASIER TO WORK WITH THAN ARE SOME OF THE ADVANCED FIBER REINFORCED COMPOSITE MATERIALS. THE MATERIAL COST IS HIGH, BUT THE OVERALL COST OF INSTALLED BERYLLIUM STRUCTURE MAY BE LOWER IN SOME APPLICATIONS THAN EQUIVALENT ONES MADE OF ADVANCED COMPOSITES. THE COMBINED PROPERTIES OF HIGH STIFFNESS, LOW WEIGHT, HIGH THERMAL CONDUCTIVITY AND HIGH TEMPERATURE CAPABILITY MAKE BERYLLIUM COMPETITIVE WEIGHTWISE WITH OTHER ADVANCED MATERIALS.

THE FUTURE OF BERYLLIUM AS A LIGHTWEIGHT STRUCTURAL MATERIAL APPEARS TO BE OVERSHADOWED BY THE RAPID DEVELOPMENT OF ADVANCED COMPOSITES. HOWEVER, SINCE MANY DESIGN AND FABRICATION DIFFICULTIES STILL EXIST IN THE STRUCTURAL APPLICATION OF THE LATTER, IT IS BELIEVED THAT, WITH SOME FURTHER DEVELOPMENT, BERYLLIUM COULD BE USED ADVANTAGEOUSLY FOR MANY STRUCTURAL ELEMENTS OF THE SPACE SHUTTLE.

ASSESSMENT OF CURRENT TECHNOLOGY

- FAVORABLE PROPERTIES : HIGH SPECIFIC MODULUS
 UNIQUE THERMAL PROPERTIES
- UNFAVORABLE PROPERTIES : BRITTLNESS
 MODERATE SPECIFIC STRENGTH
- HIGH MATERIAL COST
- LIMITED ENGINEERING EXPERIENCE
- LIMITED RESEARCH AND DEVELOPMENT ACTIVITIES
- COMPETITIVE WEIGHT WISE WITH OTHER ADVANCED MATERIALS
- FABRICATION ADVANTAGE OVER ADVANCED COMPOSITES
- MANY POTENTIAL APPLICATIONS IN A SPACE SHUTTLE VEHICLE

RECOMMENDATIONS FOR R&D

VERY LITTLE EFFORT HAS BEEN DEVOTED TO BERYLLIUM IN THE CURRENT SPACE SHUTTLE STRUCTURES AND MATERIALS TECHNOLOGY PROGRAM. SINCE WEIGHT REDUCTION WILL BE A PRIMARY CONCERN IN THE SPACE SHUTTLE DEVELOPMENT, IT IS FELT THAT A LIMITED INVESTMENT ON BERYLLIUM TECHNOLOGY TO BOOST THE SOFT AREAS OF CURRENT INDUSTRY ACTIVITIES AND TO CRITICALLY EVALUATE BERYLLIUM AS A CANDIDATE MATERIAL FOR PRIMARY AS WELL AS SECONDARY STRUCTURES WOULD BE A WORTHWHILE EFFORT TO ENSURE A RELIABLE MATERIAL SOURCE FOR A LIGHTWEIGHT VEHICLE. TO THIS END THE LISTED STUDY TASKS ARE SUGGESTED.

RECOMMENDATIONS FOR BERYLLIUM R&D

- GENERATION AND EVALUATION OF MATERIAL PROPERTY DATA AT LOW TEMPERATURES
- EFFECT OF METEOROID IMPACT, PARTICULARLY AT LOW TEMPERATURES
- FRACTURE CONTROL OF BERYLLIUM STRUCTURES
- COORDINATION AND COOPERATION WITH BERYLLIUM INDUSTRY AND OTHER GOVERNMENT AGENCIES TO GENERATE AN ENGINEERING DESIGN HANDBOOK FOR BERYLLIUM STRUCTURES
- IDENTIFICATION OF COMPLEX SPACE SHUTTLE STRUCTURAL COMPONENTS FOR WHICH BERYLLIUM CAN OUT-PERFORM ADVANCED COMPOSITES AND OTHER ENGINEERING MATERIALS
- IDENTIFICATION OF FLUTTER CRITICAL HEAT SHIELD PANELS IN A SPACE SHUTTLE VEHICLE FOR WHICH BERYLLIUM CAN BEST BE APPLIED
- IDENTIFICATION OF DESIGN AND FABRICATION PROBLEMS AND DIFFICULTIES OF BERYLLIUM PRIMARY STRUCTURES FOR A SPACE SHUTTLE
- TRADEOFF BETWEEN SELECTED STRUCTURAL ELEMENTS USING BERYLLIUM AND ADVANCED COMPOSITES



Subject: Beryllium - A Structural Material
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From: C. C. Ong

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